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INTERACTION EFFECTS OF STORAGE CAVERNS IN SALT

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ABSTRACT

The U. S. Strategic Petroleum Reserve program for crude oil stockpiling utilizes some existing solution mined caverns in Gulf Coast salt domes. Geomechanical analyses are important tools used to assess the structural stability of these caverns. This report addresses the interactions between adjacent caverns which result from maintaining different pressures in the caverns. Finite element models of two adjacent caverns are analyzed for four different cavern spacings. The brine pressure is simulated in one cavern while the pressure in the adjacent cavern ranges from that of the oil head to atmospheric conditions. Stress distributions and deformed profiles of the caverns are plotted for the conditions simulated. Since the tensile strength of salt is low (typically 100 - 300 psi), regions in which tensile stresses occur are considered to have a significant probability of

slabbing. A preliminary recommendation is made to maintain similar pressures to adjacent caverns in which the pillar thickness/cavern diameter ratio of the web between caverns is less than 0.5 unless cavern specific assessments indicate that the potential for pillar slabbing is minimal.

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INTRODUCTION

The need for an emergency storage program for petroleum supplies was demonstrated during the partial interuption of foreign oil applies in the winter of 1973-74. Severe economic impacts were felt on the U. S. economy, and our vulnerability to interruptions was emphasized by the ensuing loss of $34-45 billion in gross national product and 500,000 jobs [1]. The Energy Policy and Conservation Act (EPCA) passed by Congress authorized the creation of a Strategic Petroleum Reserve (SPR) consistent with a plan developed by the Federal Energy Administration. The Department of Energy (DOE) now has the responsibility for implementing the SPR plan.

Salt is an attractive material for cavern construction and crude-oil storage since, in general, it is relatively pure, impervious to hydrocarbon liquids and gases, homogeneous (not significantly interbedded with other types of rock), can be readily dissolved (leached) by water, and has adequate strength and ductility properties. To meet the time requirements mandated for the SPR program, existing solution mined caverns in.Gulf Coast salt domes are being used for crude-oil storage.

Future storage of oil will also take place in a conventional underground mine and in newly leached caverns in salt domes. In all cases, the structural integrity of the storage facility must be evaluated to ensure: 1) that the facility is stable in its current configuration, 2) that the petroleum products cannot escape during storage, and 3) that the operating plans will not significantly degrade either the stability or the pressure tightness of the caverns. For the existing caverns, the structural integrity of a cavern is affected by the properties of the salt (and in some cases, other nearby strata) surrounding the cavern, the shape of the cavern, and its location within the salt dome.

Three aspects of cavern location are considered to be of fundamental importance:

1. cavern location relative to the edge of the salt dome,
2. cavern location relative to the top of the salt, and
3. cavern location relative to adjacent caverns.

This report details the results of a preliminary analysis of only the cavern to cavern interaction effects'as the spacing between caverns is varied for different loading conditions.

The normalized parameter, P/D is used to compare different cavern spacings, where P is the wall thickness (pillar size) between the caverns and D is the cavern diameter. Under normal operating conditions, an oil pressure is maintained at the surface to provide a pressure at the oil-brine interface in the cavern which is equivalent to a brine head to the surface. The worst loading condition which the pillar material could see, therefore, occurs when different pressures are maintained in adjacent caverns. If well maintenance or work-over is to be done, the oil well head pressure may have to be lowered to zero; similarly, accident conditions could result in a loss of this wellhead pressure. An extreme, although much less likely, loading condition is that an adjacent cavern may be depressurized to atmospheric conditions. This condition could be approached if the column of fluid to the surface is lost due to either a casing failure or grout deterioration or if the product stored in the adjacent cavern is a gaseous hydrocarbon (i.e., ethane, methane, etc.) which could be removed (either intentionally or accidentally) by an expansion process to nearly atmospheric conditions. The pillar width between caverns will decrease during SPR operations due to the leaching action of the fresh or raw water injected into the cavern during withdrawal. Each raw water injection cycle could increase the cavern volume by about 15%.

In the next section of this report, the existing caverns in the SPR program are described and important geometrical parameters are noted along with government regulations and industrial standards pertaining to leached caverns. Finite element models used in this study are then described, and a discussion of the numerical predictions of the deformation and stress fields is provided. Conclusions and recommendations drawn from this study are detailed in the final section;

SPR CAVERN DESCRIPTION

Current plans in the SPR program call for the utilization of existing caverns (originally developed for brine production) in four domes: West Hackberry, Bayou Choctaw, and Sulphur Mines domes in Louisiana; and the Bryan Mound dome in Texas. Tables l-4 were developed to provide the pertinent parameters for the SPR caverns and, in some instances, for other caverns at these sites. which might impact the use of existing caverns or the construction of new ones. Quite obviously, the variation in the parameters for the SPR caverns is substantial.

The cavern volumes range from about 3 MMB (million barrels) to more than 33 MMB. The heights vary from 153 ft to 2130 ft; diameters range from 220 ft to 839 ft. The tops of the caverns are from 1450 ft to 3980 ft below the surface while maximum depths are between 1670 ft and 4306 ft. The cross-sectional views of the caverns shown in Figures 1 – 4 demonstrate clearly the variations of these caverns from regular shapes, i.e., from cylinders, spheres, ellipsoids, etc., and indicate the current spacing of some of the caverns. Since the location of a cavern relative to the distance (both vertically and horizontally) to the dome boundaries and to adjacent caverns determines in large part the suitability of a cavern (from a geomechanics viewpoint) for storage, these data have also been recorded in Tables 1 – 4. The data presented in these tables were obtained primarily from the cavern certification documents [2 – 16] and

TABLE 1 BRYAN MOUND SPR CAVERNS

BRYAN MOUND

Cavern Number	Year Constructed	Volume (mmb)	Oil Stored (mmb)	Type of Oil	DEPTHS - ft: Top of Caprock	Top of Salt	Casing Seat	Top of Cavern	Bottom of Cavern	Cavern Diameter, D	Cavern Height, H	H/D	Nearest Cavern	Distance to Nearest Cavern, P	P/D	Roof Thickness, B	B/D	Distance to Dome Edge, E	E/D	Comments
1	194	6.6	5.9	Swee	580*	1136*	147	234'	2810	440	465	1.06	#4	220	.50	120	2.75	>50	>1.14	Close to cavern #4.
2	195	5.9	5.0	Swee	580*	1136'	145	145	1670	584	220	.38	#3	300	.51	31	.54	200	3.42	Relatively low B/D ratio. Casing seat is at cavern roof.
4		6.3	4.8	Swee	580*	1136*	191	2551	3108	749	553	.74	#1	220	.29	141	1.89	230	3.07	Large vertical separation between caverns 3 and 4. Close to cavern 1.
5		3.3	2.5	See	580*	1136'	191	213	3285	491[a] 733[a]	595 515/115	1.21[a] .70[a]	#4	334	.46	99	1.36	170	2.32	A shale stringer may exist in the hourglass section of this cavern. Ceiling trap (1.3 mmb) in lower chamber may be minimized by directionally drilled reentry well. Largest cavern in SPR program.
3[b]					580*	1136*														Cavern appears to be self-leaching with communication with the caprock.

* Top of caprock and salt depths are estimated; this information will be determined for other areas in the dome as part of the expansion well drilling program.

a. Cavern 5 has two lobes (one on top of the other) which provide an hourglass shaped cavern. The diameter of the lower lobe is used to determine the P/D, B/D, and E/D ratios.

b. This cavern is not in the ESR program but has a potential impact on ESR caverns.

NOTE: All distances are given in feet.

TABLE 2 WEST HACKBERRY SPR CAVERNS

WEST HACKBERRY

Cavern Number	Year Constructed	Volume (mmb)	Oil Stored (mmb)	Type of Oil	DEPTHS - ft: Top of Caprock	Top of Salt	Casing Seat	Top of Cavern	Bottom of Cavern	Cavern Diameter, D	Cavern Height, H	H/D	Nearest Cavern	Distance to Nearest Cavern, P	P/D	Roof Thickness, B	B/D	Distance to Dome Edge, E	E/D	Comments
a	1946	12.2	6.5	Sour	.598	1949	632	1237	395	339	153	.18	#9	315	.38	288	..54	700	.83	Longest flat roof span in single cavity in ESR program.
7	1946	12.3	2.8	Sweet	1551	1965	2400	2542	1498	430	956	2.22	#6	700	1.63	577	1.34	>1000	>2.33	Only cavern at West Hackberry in which sweet crude is currently stored. Top 600' is cylindrically shaped; lower 350' is spherical. Well isolated from top of dome and nearby caverns.
8	1946	10.1	2.[illegible]	Sour	1515	1991	2402	2440	1451	446	.011	2.27	#9	160	.36	449	1.01	>1000	>2.21	Will coalesce (after 3 cycles) with cavern 9.
9	1947	8.9	23	Sou[illegible]	155	215[illegible]	240[illegible]	321[illegible]	3561	588	351	.60	#8	160	.2	105	1.8	NA*	NA*	Will coalesce (after 3 cycles) with cavern 8.
11	1962	8.[illegible]	65	sou[illegible]	152	2056	279[illegible]	294[illegible]	3760	306	815	2.66		>1000	3.2	88	2.91	>100[illegible]	>3.27	Cavity represents a prototype of the planned expansion cavities (i.e., cavity is cylindrically shaped with 306' maximum diameter while new cavities will have 270' maximum diameter). Cavern is well removed from the caprock, dome edge and other cavities.

NA* - Not applicable since another cavern is between #9 and dome edge.

NOTE: All distances are given in feet.

TABLE 3 BAYOU CHOCTAW SPR CAVERNS

ESR Storage Caverns — BAYOU CHOCTAW

DEPTHS - ft

Cavern Number	Year Constructed	Volume (mmb)	Oil Stored (mmb)	Type of Oil	Top of Caprock	Top of Salt	Casing Seat	Top of Cavern	Bottom of Cavern	Cavern Diameter, D	Cavern Height, H	H/D	Nearest Cavern	Distance to Nearest Cavern, P	P/D	Roof Thickness, B	B/D	Distance to Dome Edge, E	E/D	Comments
15	1953	15.7	11.6*	Sour	477	637	2560	2597	3297	350 480[a]	700	2.0	17	57-100'	.16-.29	2000	5.71	>600	>1.71	Extremely close to cavern 17 which contains ethane @ 2000 psi.
18	1967	8.5	3.8*	Sour	430	850	1176	2110	4240	385	2130	5.53	17	380	.99	1260	3.27	780	2.03	This cavern could potentially be effected by uncontrolled leaching of cavern 17.
19	1967	7.5	5.1*	Sour	550	850	2305	2995	4270	264	1275	4.83	16	450	1.7	2145	8.13	500	1.89	Certified as usable for 5 cycles pending information obtained regarding current shape of cavern 16 and future operational plans.
20	1970	5.2	---	---	500	680	1085	3980	4306	525	380	.72	NONE CLOSE AT DEPTH			3299	6.28	135	.26	Close proximity to dome edge precludes more than 1 fresh water cycle.

*Oil stored as of 2/12/79.

a. Diameter used in SAI cavern stability study.

General Site Comments - Poor quality, thin caprock (mostly gypsum) exists at this site. Major drilling problems were experienced due to loss of circulation near salt/caprock interface and presence of gas in salt-caprock interface. Additional costs and delays should be anticipated at this site for drilling reentry wells and expansion wells.

NOTE: All distances are given in feet.

TABLE 4 SULPHUR MINES SPR CAVERNS

SULPHUR MINES

Cavern Number	Year Constructed	Volume (mmb)	Oil Stored (mmb)	Type of Oil	DEPTHS - ft: Top of Caprock	Top of Salt	Casing Seat	Top of Cavern	Bottom of Cavern	Cavern Diameter, D	Cavern Height, H	H/D	Nearest Cavern	Distance to Nearest Cavern, P	P/D	Roof Thickness, B	B/D	Distance to Dome Edge, E	E/D	Comments and Recommendations
2	1946	6.2	*	*	500	1460	1562	2447	3086	400	639	1.6				987	2.47			
4	1949	2.9	*	*	819	1620	1640	2793	3115	420	322	.77				1173	2.79	364'	.87	
5	1953	3.3	*	*	829	1480	1714	2448	3450	220	1002	4.55	Allied #2 Well PPG #1-A	380' 250'	1.73 .63	968	4.4	—	—	Caverns 2-4-5 have already coalesced. Total storage volume in the 3 cavities is 12.3 mmb. Solution channels exist between 4 and 5 at 2900' and between 2800-2900' for caverns 5 and 2. Certified for only 2 cycles of use. Distance from cavern 2-4-5 gallery to 6-7 gallery is 310'. Major diameter for 2-4-5 gallery is 1140'; minor diameter is 585'; maximum height 1002'. The jagged cavern profiles clearly indicate layers of highly soluble material.
6	1955	5.1	*	*	620	1470	1836	2968	3401	618	433	.70	#7	100'	.16	1498	2.42	33[a] 50[b]	.73	Because of their closeness, caverns 6 and 7 are treated as a single gallery. Unusual shape, have long radii alternating with small diameter necks.
7	1957	5.6	*	*	962	1500	1822	2790	3195	497	405	.81	#6	100'	.20	1290	2.6	235[a] 180[b]	.47 .36	

*No oil is currently stored at the Sulphur Mines site.

a. Distance given in site certification document.

b. Distance given is site report by PB/KBB.

General Site Comments - The presence of highly soluble lenses of material is somewhat unusual in Gulf Coast domes. Predictions of cavern enlargement should consider these high soluble regions. The uncertainties regarding the location of dome boundaries, the lack of operating experience with a cavity of the size of the 2-4-5 gallery, and the potential for slabbing of ledge material mandate that careful consideration be given to establishing operating procedures which will minimize potential withdrawal problems or delays and necessitate additional geotechnical work to assess the viability of failure scenarios. This is the only site currently considered in the ESR program in which additional caverns may be developed by other than SPR personnel below the storage caverns. An easement would permit construction below 4000' but would prohibit spans greater than 500', distances between cavern walls of less than 200' and cavern roofs flatter than 30° from the horizontal.

NOTE: All distances are given in feet.

BAYOU CHOCTAW - Iberville Parish, Louisiana

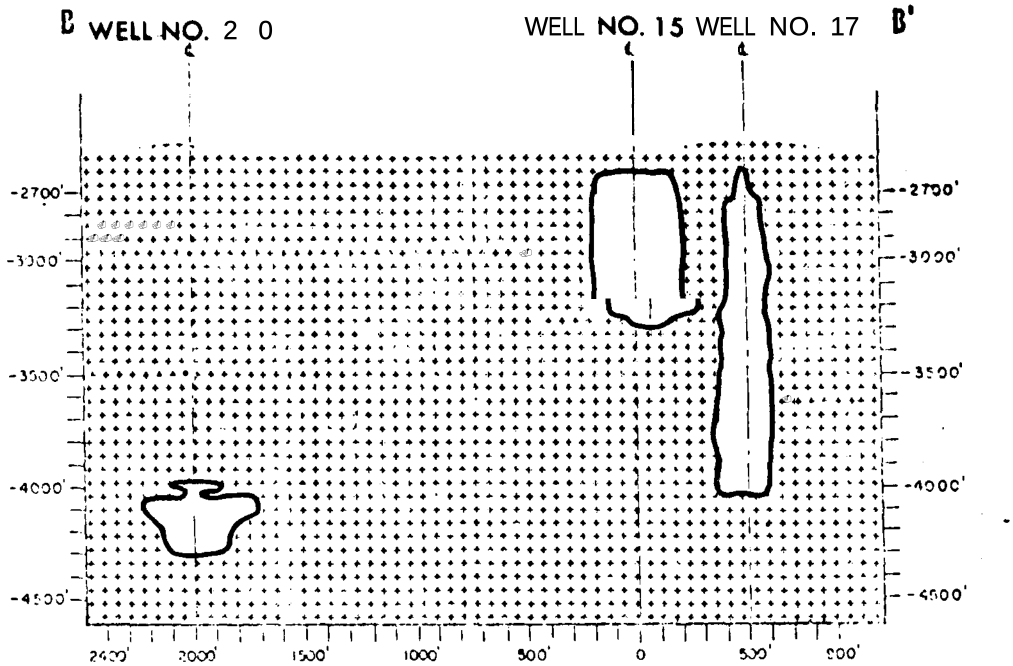


FIGURE 1. CROSS SECTION OF CAVERNS AT BAYOU CHOCTAW

SULPHUR MINES - Calcasieu Parish, Louisiana

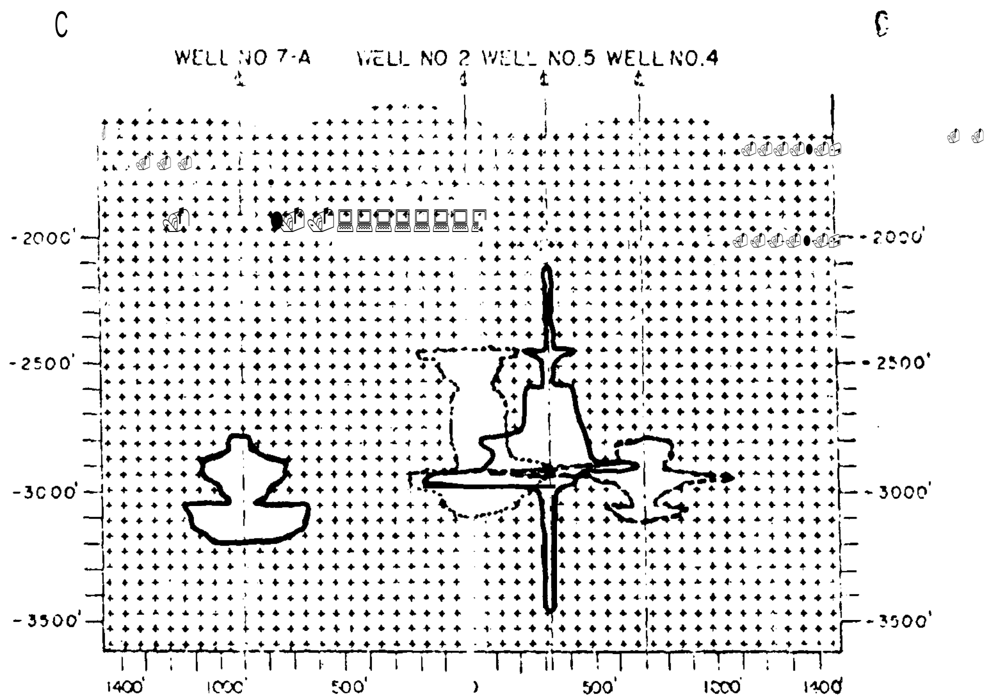


FIGURE 2. CROSS SECTION OF SULPHUR MINES CAVERNS

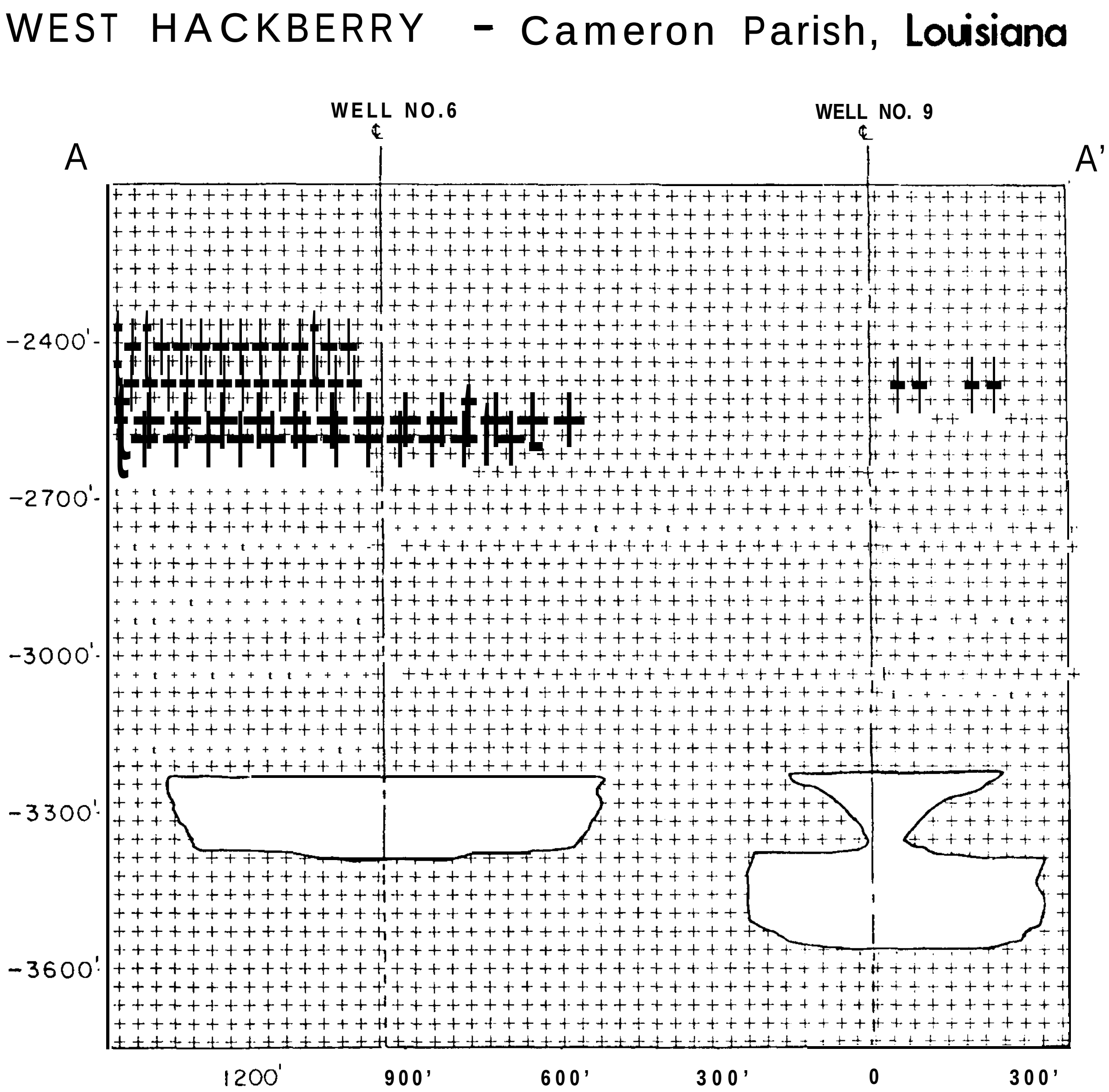


FIGURE 3. SONAR BASED PROFILE OF CAVERNS #6 AND #9 - WEST HACKBERRY SITE

WEST HACKBERRY - Cameron Parish, Louisiana

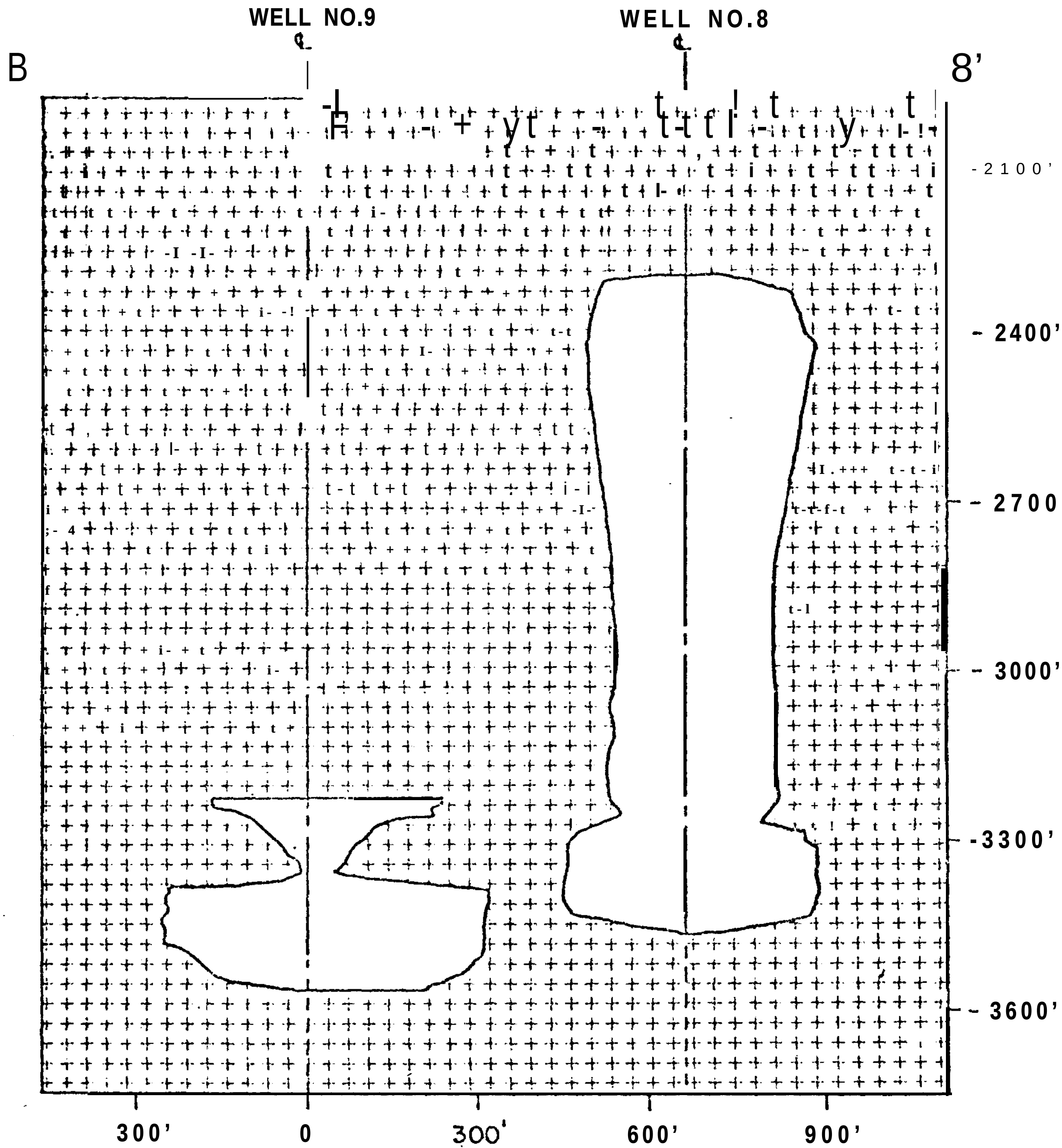


FIGURE 4. SONAR BASED PROFILE OF CAVERNS #8 AND #9 - WEST HACKBERRY SITE

from other SPR contractor generated documents [17 - 26].

Since the pillar or web thickness, P, can be used as a measure of the likelihood for cavern coalescence it is used, for comparison purposes, with the standards set by the state of Louisiana [27] and the Gas Producer's Association [28]. A cavern separation distance of 200 ft is required for new caverns constructed in the state of Louisiana. The Gas Producer's Association standard requires only 100 ft between caverns. While the new SPR caverns will at all times have wall thicknesses in excess of 200 ft several of the ESR (Early Storage Reserve) caverns will not maintain this spacing during the five storage cycles for which the SPR system is designed to operate. Specifically, the 200 ft spacing will not be maintained at Bryan Mound between caverns #1 and #4, at Bayou Choctaw between caverns #15 and #17, at West Hackberry between caverns #8 and #9 and at Sulphur Mines between caverns #6 and #7.

Coalescence is expected in several of the caverns during crude oil cycling of the reserve. Analytical calculations in Reference 20 suggest that the region between many of the existing caverns is, because of the spacing, currently in a state of plastic or brittle behavior.* These calculations are based upon formulas developed [29,30,31] for cylindrical

*The terminology from Reference 20 "plastic or brittle" behavior implies irreversible damage.

caverns with hemispherical or arch-shaped roofs. The extent of the postulated plastic and brittle zones of salt response near each cavern is calculated by assuming that each cavern is isolated from its neighbors. Cavern to cavern interference effects are then assessed by superposition of results from isolated cavern analyses. The authors of Reference 20 mention that their equations are not valid for conditions in which two adjacent caverns experience different pressures. Although it is postulated in Reference 20 that the effect of a pressure differential between caverns would be of second order compared with the effects of either cavern's hydrostatic pressure, it is stated that "in cases where the wall is already near its buckling point, however, the application of such an unbalance force could possibly initiate wall failure and thus should be avoided."

While it is possible to envision that catastrophic failure of caverns could occur as a result of coalescence, the most probable effects seem to be slabbing of the pillar section between caverns and the loss of an oil blanket* if a higher

*Current design of caverns for oil storage requires that oil be in contact with the cavern roof to prevent further leaching in this region.

cavern washes into a lower one. Slabbing could either damage the brine strings by direct contact or could create flow patterns-in the stored liquid which would damage the brine strings in the cavern. In the French hydrocarbon storage program [32], it was reported that the insoluble materials (primarily anhydrite) which were formerly stratified broke away from the walls during dissolutioning. It was further implied that the eddies created by these chunks of insoluble material caused damage to the tubing strings. The analyses performed in this study predict (without relying upon superposition of isolated cavern results) the stresses and deformations in the pillar material and assess the potential for slabbing of the salt in this region.

FINITE ELEMENT STRESS ANALYSES OF ADJACENT CAVERNS

Finite element calculations have been performed to simulate the interaction of two adjacent caverns at various wellhead pressures. Results are reported for analysis of the cavern interaction problem with the following geometric parameters for two identical caverns:

elevation of top of cavern	-3200 ft
height of cavern (h)	600 ft
diameter of cavern (D)	300 ft
web thickness between caverns (P)	60, 150, 300, 600 ft

The three-dimensional geometry of the two cavern problem is approximated by two plane strain idealizations. The first problem treats the vertical cross section of the modeled geometry; a typical grid pattern is shown in Figure 5. The second idealization is from the plan view with a typical grid pattern exhibited in Figure 6. The purpose of these idealizations is to reduce the numerical complexity of the problems to be solved. It is expected that the plane strain idealization of the vertical cross section will predict larger

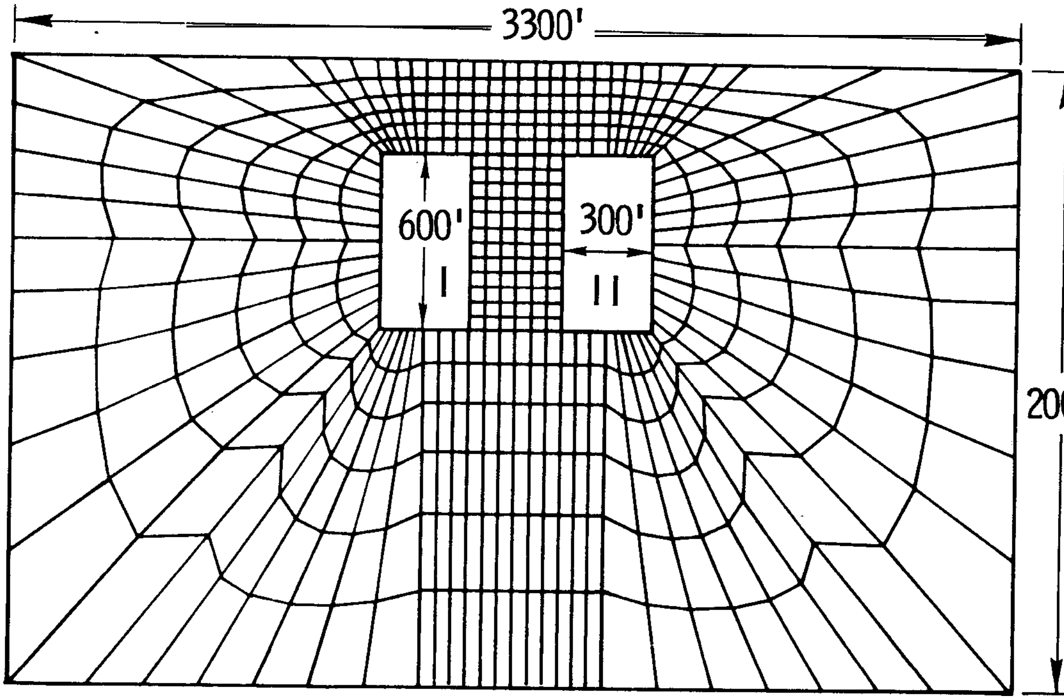


FIGURE 5. TYPICAL GRID PATTERNS FOR VERTICAL IDEALIZATION

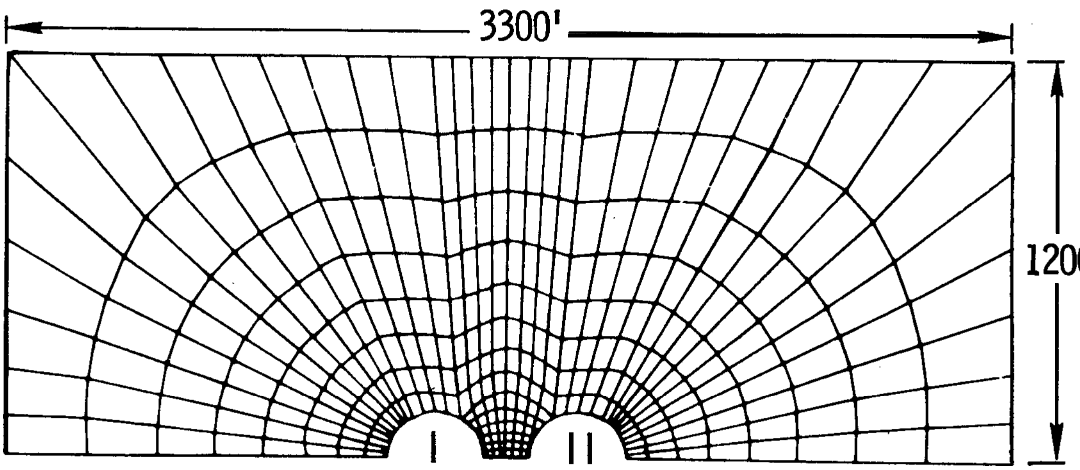


FIGURE 6. TYPICAL GRID PATTERNS FOR HORIZONTAL IDEALIZATION

than actual web deformations and, as such, will yield conservative information for application. However, since the same approximation is to be made for each web thickness analyzed, the results will show trends and relative influences. The plan view idealization of the cavern interaction problem may result in more accurate predictions, especially for caverns with larger height-to-diameter ratios. This idealization does not, however, account for variation of overburden pressure with depth nor does it simulate the vertical stress concentration near the edge of the caverns.

The analysis presented in this paper employs an elastic-perfectly plastic material model with a Drucker-Prager yield surface. The relevant material parameters for the salt are taken from tests on Weeks Island salt [33] as

$$\phi = 56°, \; c = 330 \text{ psi}.$$

The elastic properties used in the analysis were

$$E = 2.0 \times 10^6 \text{ psi}, \; \nu = 0.42$$

Calculations were performed using the ADINA code [34] employing both small and large deformation options as appropriate.

The plane strain analysis for the vertical cross section (Figure-S) employs the following loadings:

1. Exterior boundaries are subjected to overburden pressures including appropriate variation with depth. These edges are further constrained to remain straight.

2. Gravity loading is included in the form of equivalent body forces.

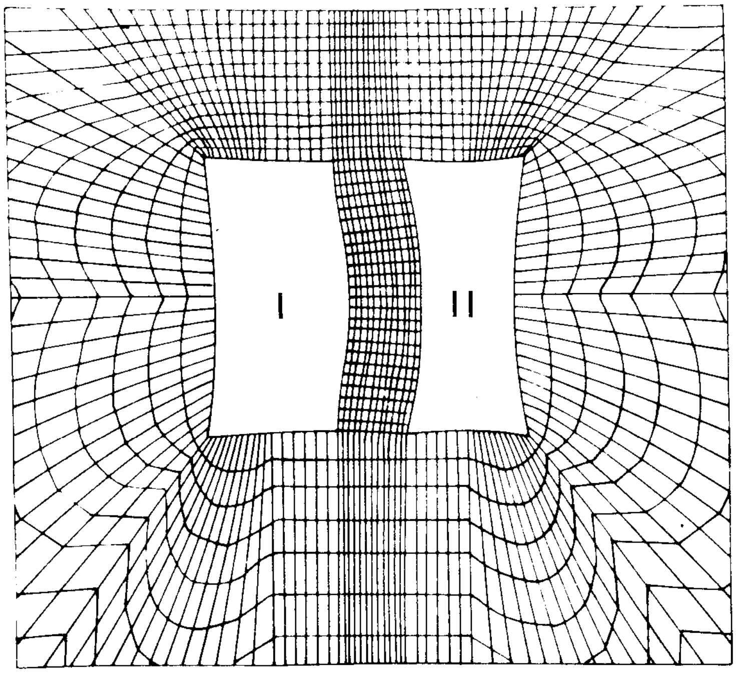
The horizontal crosssection analyses, Figure 6, include an equivalent overburden pressure loading on exterior edges. For each case, cavern I is maintained at the brine head pressure at all points while the pressure in cavern II is reduced to (a) the oil head pressure and (b) atmospheric pressure.

The numerical results presented in the next section are based on the large strain option in ADINA. The large deformation version of ADINA failed to converge for the smallest web thickness considered, i.e., 60 feet. Thus, the results to be reported for that particular case are of questionable validity. They are included to show that large displacements and possible failures should be expected for this configuration.

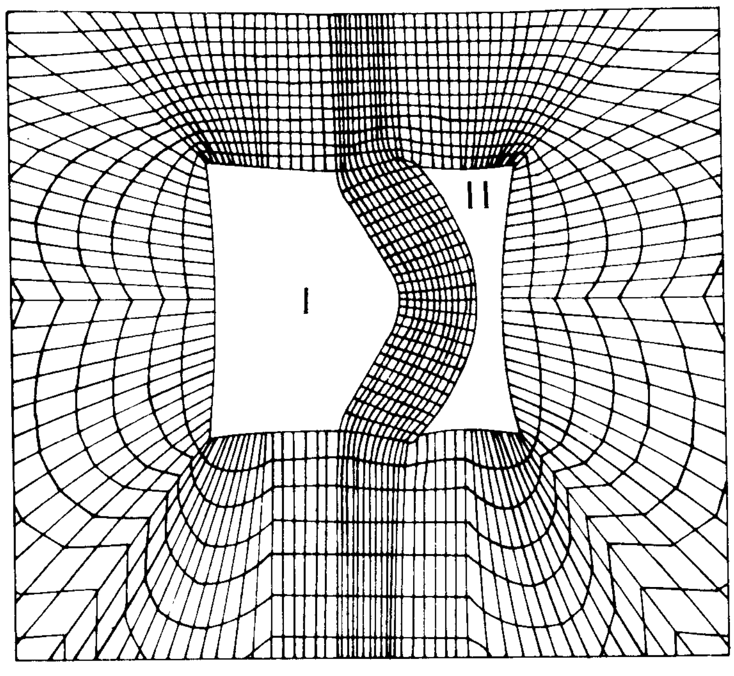
NUMERICAL PREDICTIONS FOR CAVERN DEFORMATIONS AND RELATED STRESS FIELDS

The deformed grid patterns and contour plots of von Mises stress, maximum principal stress, and mean stress (pressure) are presented (Figures 7-10) for the finite element analysis of the vertical idealization with a 150 feet pillar. Cavern I is at the brine head pressure (1750 psi) and cavern II is at (a) the oil head pressure (1280 psi) and (b) at atmospheric pressure. Similar plots of deformed crosssections and maximum principal stress are presented in Figures 11 and 12 for the horizontal idealization under the same pressures and for the same pillar thickness. Note that the character of the results are similar but that the plan view analysis predicts smaller deformations and smaller maximum principal stresses. In this case, the vertical idealization analysis predicts small regions in tension when cavern II is at zero pressure; while, the horizontal model analysis predicts no tensile regions.*

*As a basis for interpreting these results, it is generally assumed that salt has practically no tensile strength and that regions in which the maximum principal stress, sig max, is greater than zero are likely to fail by slabbing or cracking.

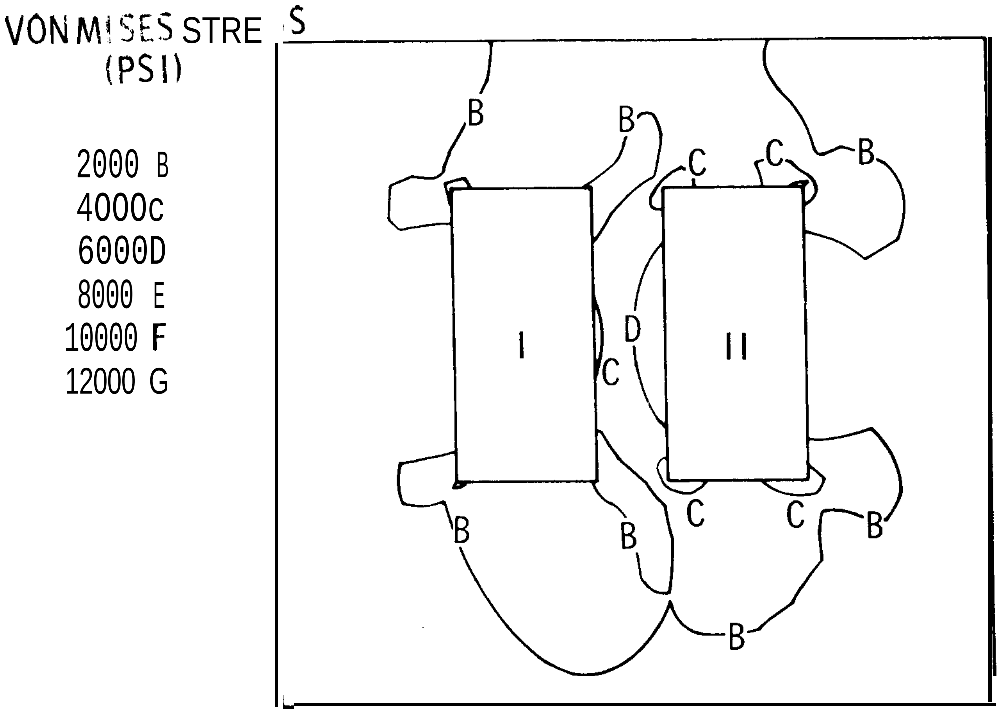


a. CAVERN II IS AT OILHEAD PRESSURE

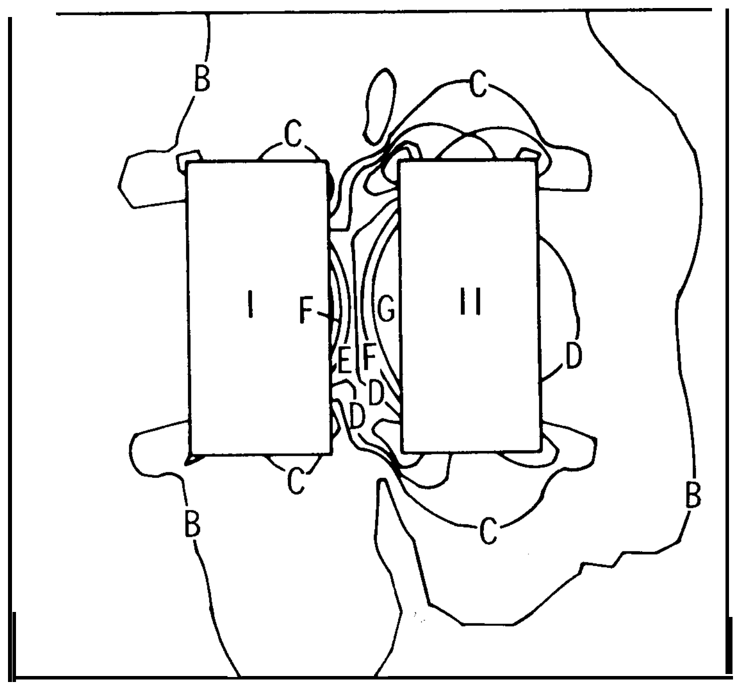


b. CAVERN II IS AT ATMOSPHERIC PRESSURE

FIGURE 7. DEFORMED GRIDS PATTERNS, P/D = 0.5
(DEFORMATIONS ARE MAGNIFIED 54 TIMES)



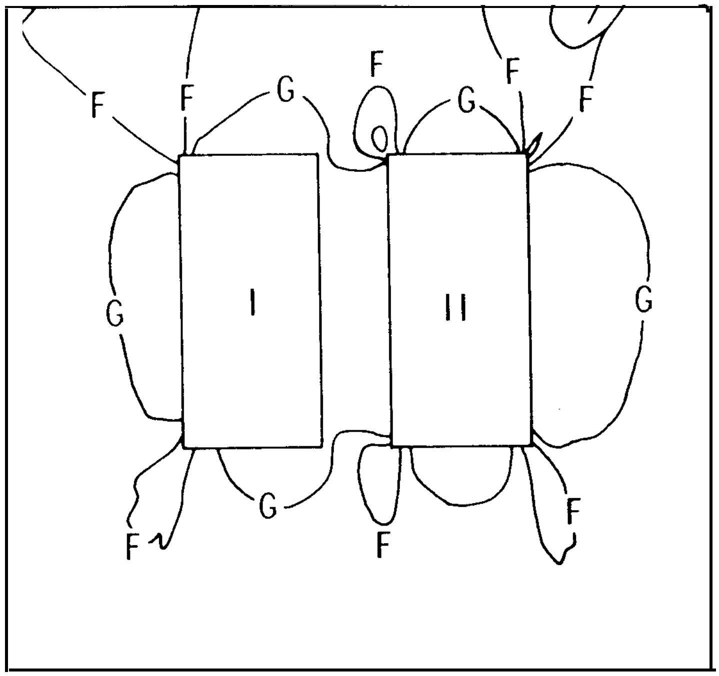
a. CAVERN I IS AT OILHEAD PRESSURE



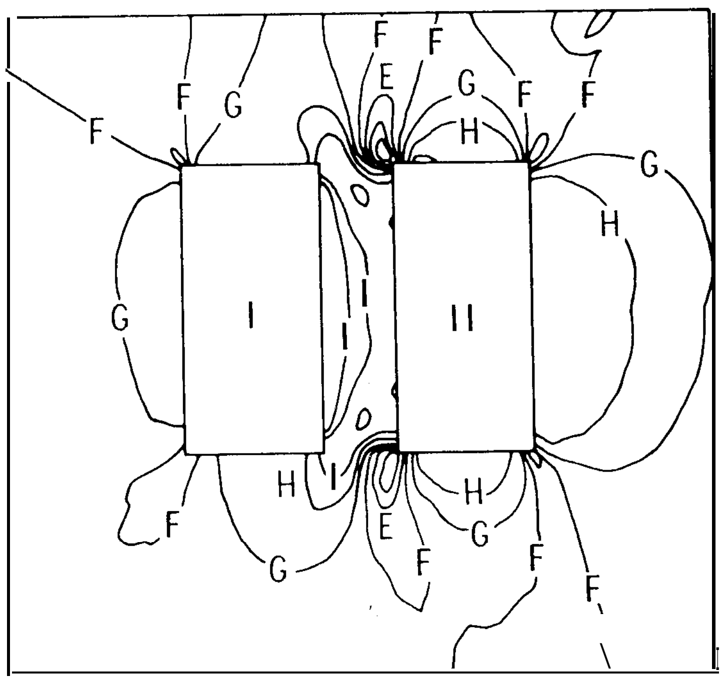
b. CAVERN II IS AT ATMOSPHERIC PRESSURE

FIGURE 8. VON MISES STRESS CONTOURS, P/D = 0.5

MAXIMUM PRINCIPAL
STRESS (PSI)
-3000 F
-2000 G
-1000 H
0 I

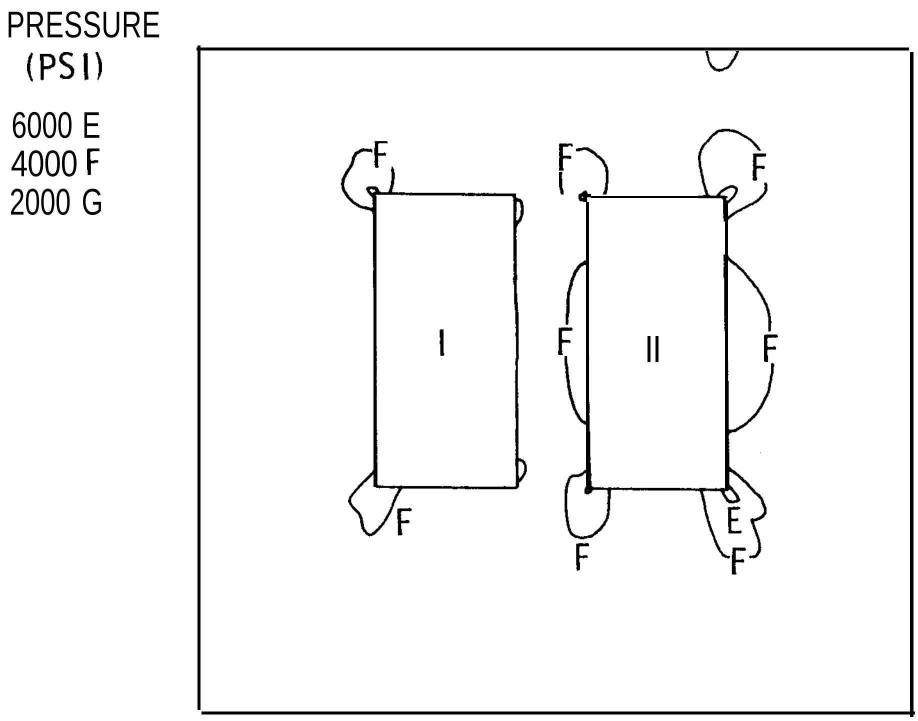


a. CAVERN B IS AT OIL HEAD PRESSURE

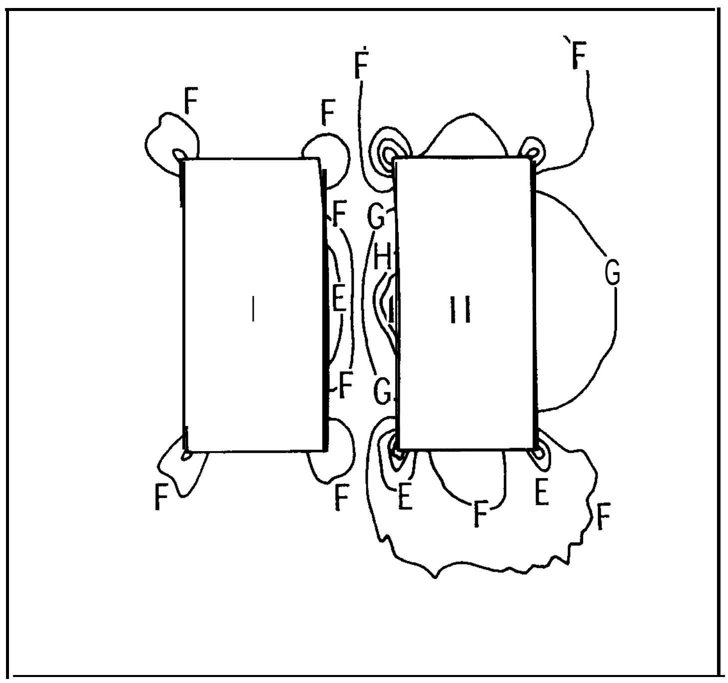


b. CAVERN B IS AT ATMOSPHERIC PRESSURE

FIGURE 9. MAXIMUM PRINCIPAL STRESS CONTOURS, P/D = 0.5

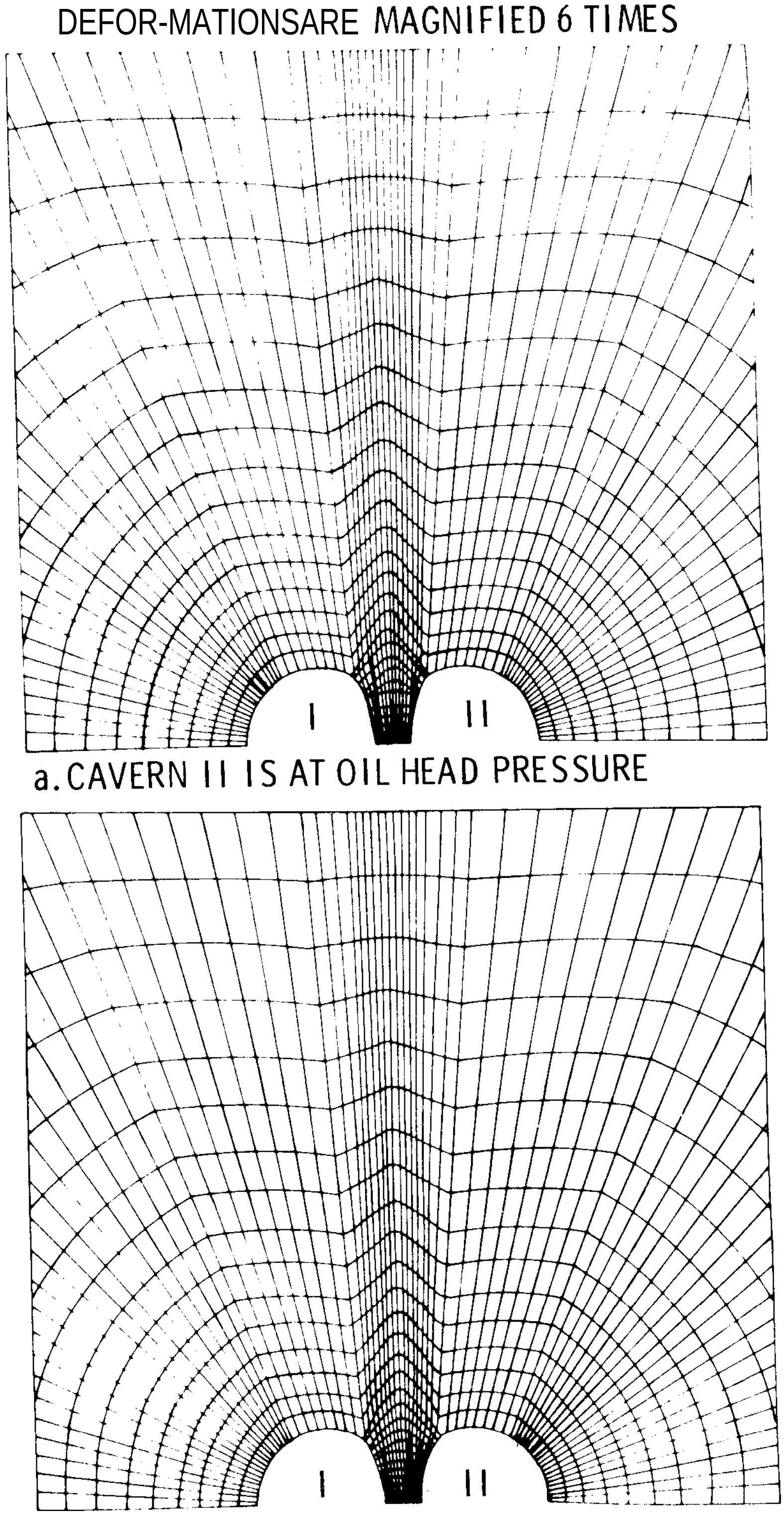


a. CAVERN II IS AT OIL HEAD PRESSURE



b. CAVERN II IS AT ATMOSPHERIC PRESSURE

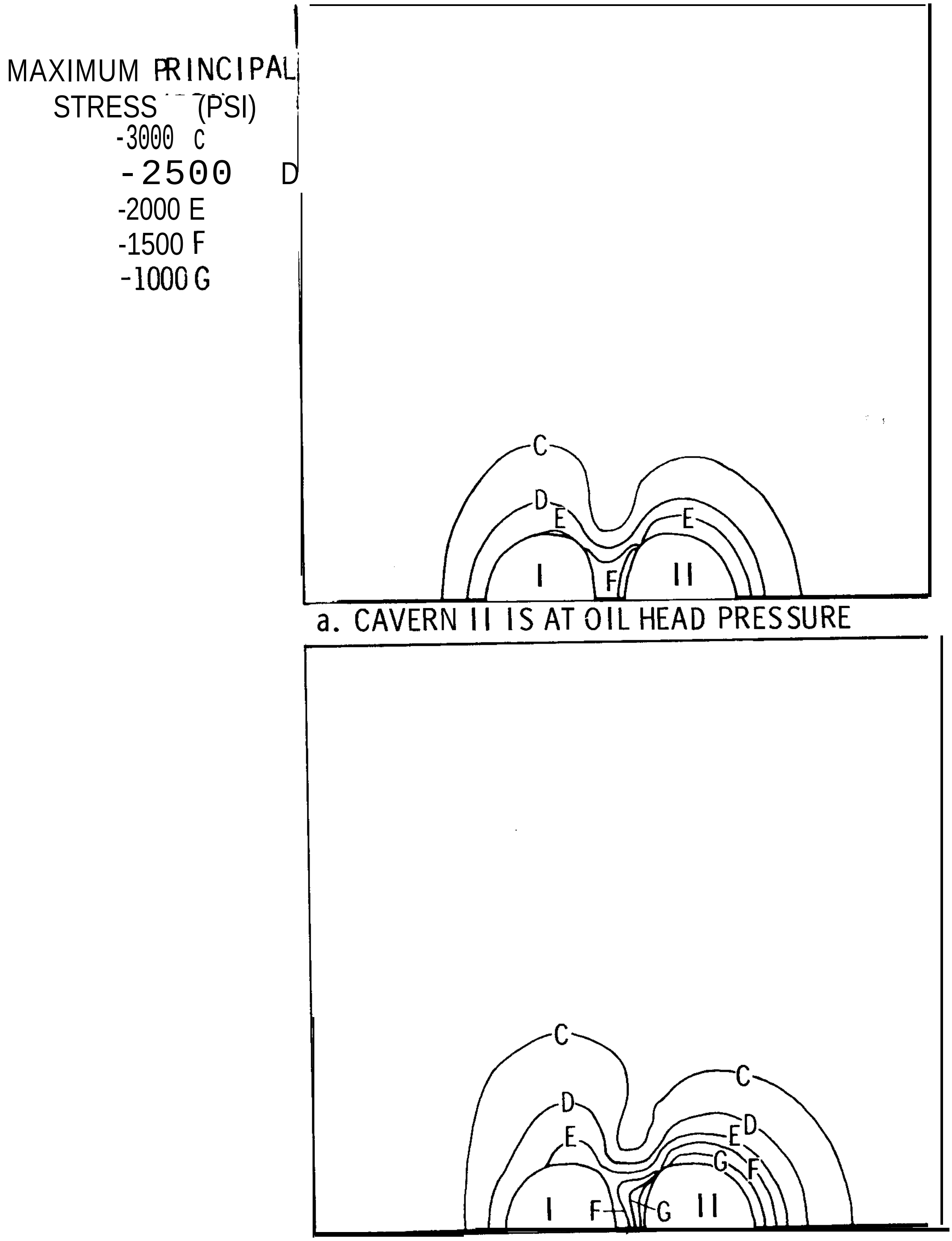
FIGURE 10. PRESSURECONTOURS, P/D = 0.5



a. CAVERN II IS AT OIL HEAD PRESSURE

b. CAVERN II IS AT ATMOSPHERIC PRESSURE

FIGURE 11. DEFORMED GRID PATTERNS FOR HORIZONTAL IDEALIZATION, P/D = 0.5



a. CAVERN II IS AT OIL HEAD PRESSURE

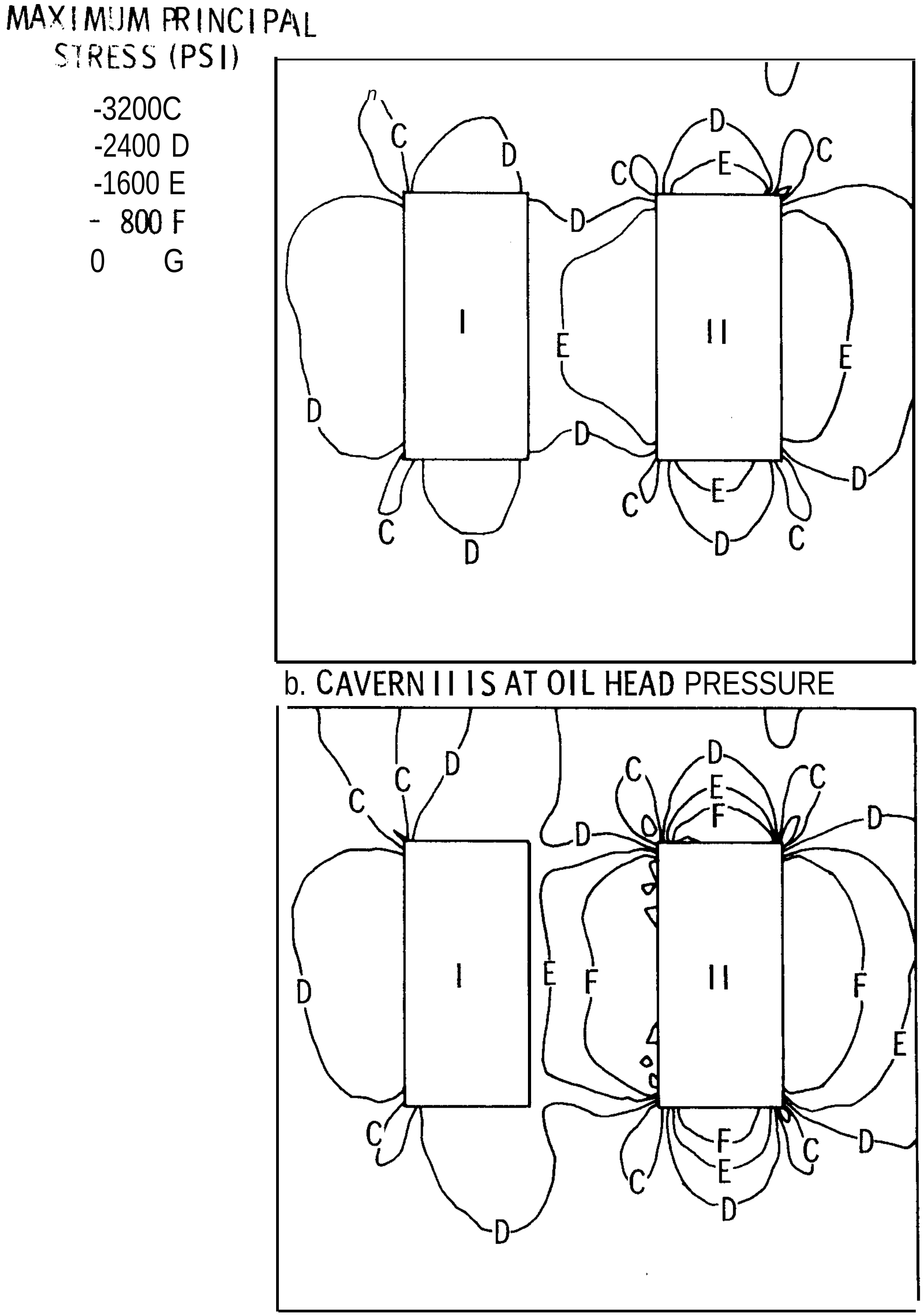
b. CAVERN II IS AT ATMOSPHERIC PRESSURE

FIGURE 12. MAXIMUM PRINCIPAL STRESS CONTOURS FOR HORIZONTAL IDEALIZATION, P/D = 0.5

Contour plots of maximum principal stress for web thicknesses of 300 and 600 feet developed with the vertical idealization are shown in Figures 13 and 14. These plots show the expected result that increases in the maximum principal stress in each of these cases are compressive except at a few isolated points. Thus cavern integrity is expected to be retained even during depressurization for configuration shown in Figures 13 and 14.

The calculated responses for a 60 foot cavern separation are shown in Figures 15-17. Figure 15 contains contour plots of maximum principal stress in the deformed state for the vertical model. Note both the large deformations and the size of the regions (shaded zones) at zero or positive maximum principal stress. These results can only be used in a qualitative fashion as the small strain assumptions employed are clearly violated. They do, however, indicate that substantial failures should be anticipated upon depressurization.

Results from the horizontal model analysis support these conclusions. Figure 16 shows deformed grid patterns and Figure 17 is a plot of maximum principal stress contours.



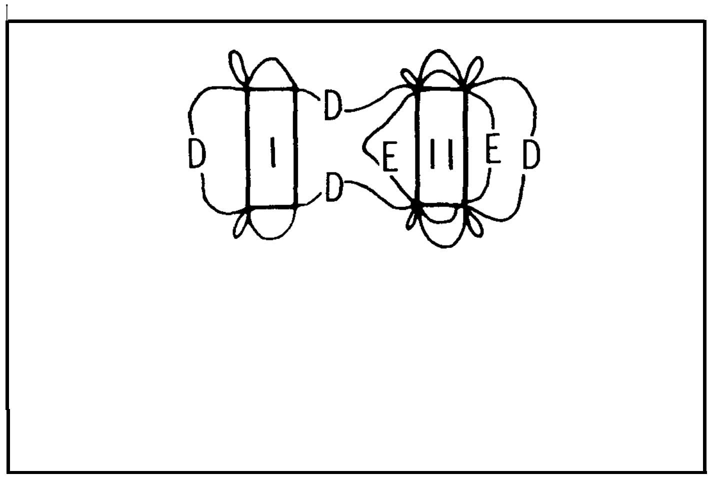
b. CAVERN II IS AT OIL HEAD PRESSURE

a. CAVERN II IS AT ATMOSPHERIC PRESSURE

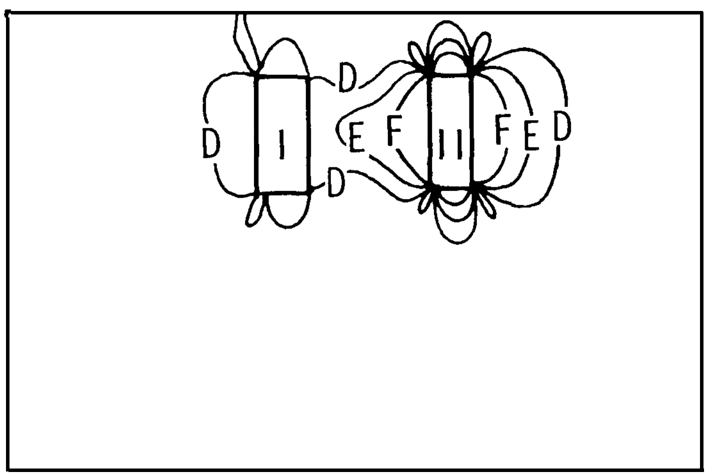
FIGURE 13. MAXIMUM PRINCIPAL STRESS CONTOURS, P/D= 1.0

MAXIMUM PRINCIPAL STRESS (PSI)

-2400 D
-1600 E
- 800 F

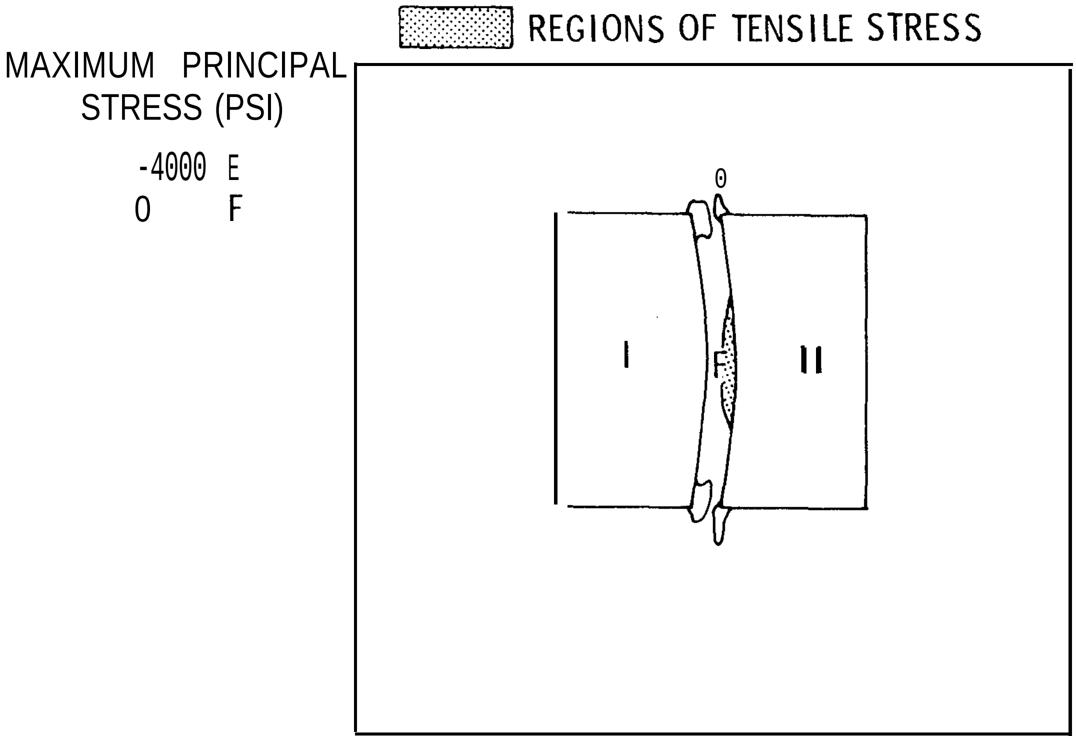


a. CAVERN II IS AT OIL HEAD PRESSURE

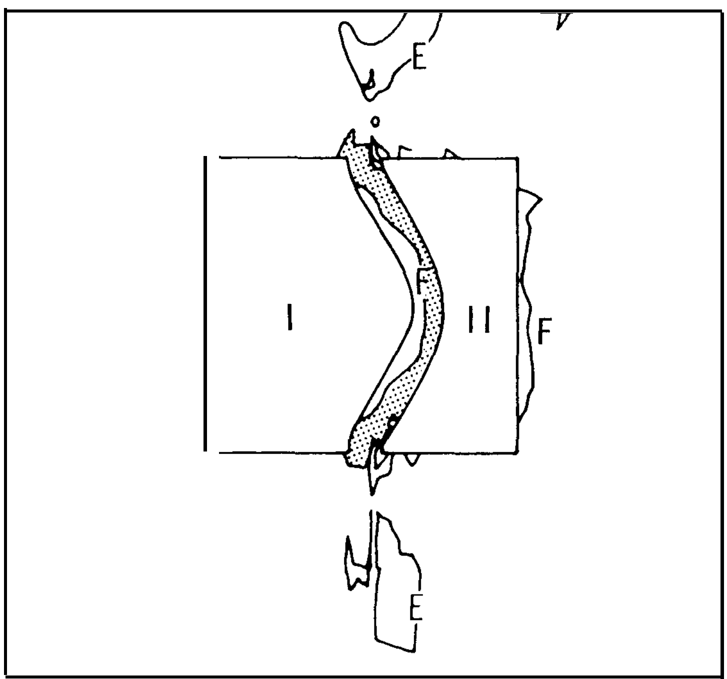


b. CAVERN II IS AT ATMOSPHERIC PRESSURE

FIGURE 14. MAXIMUM PRINCIPAL STRESS CONTOURS, P/D = 2.0



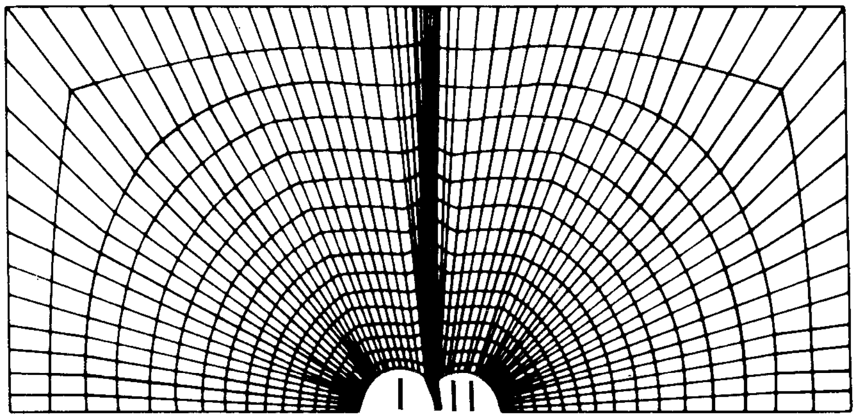
a. CAVERN I I IS AT OIL HEAD PRESSURE



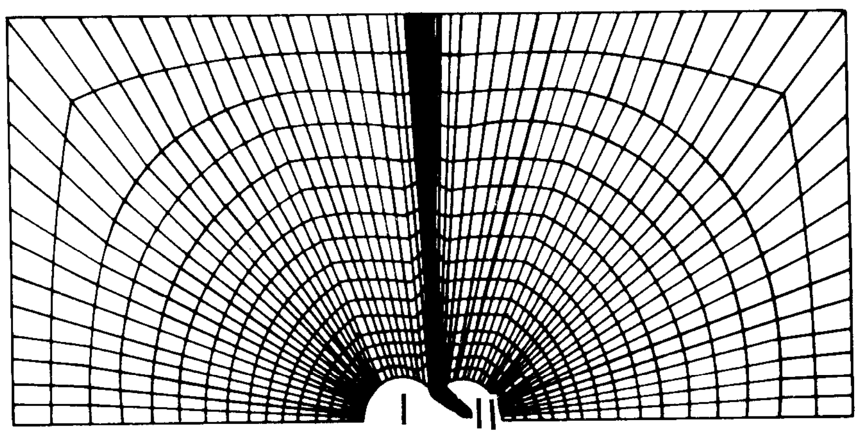
b. CAVERN I I IS AT ATMOSPHERIC PRESSURE

FIGURE 15. MAXIMUM PRINCIPAL STRESS CONTOURS, P/D = 0.2
PLOTTED IN MAGNFIED DEFORMED GEOMETRY

DEFORMATIONS ARE MAGNIFIED 30 TIMES



a. CAVERN I I IS AT OIL HEAD PRESSURE



b. CAVERN I I IS AT ATMOSPHERIC PRESSURE

FIGURE 16. DEFORMED GRID PATTERNS FOR HORIZONTAL IDEALIZATION, P/D = 0.2

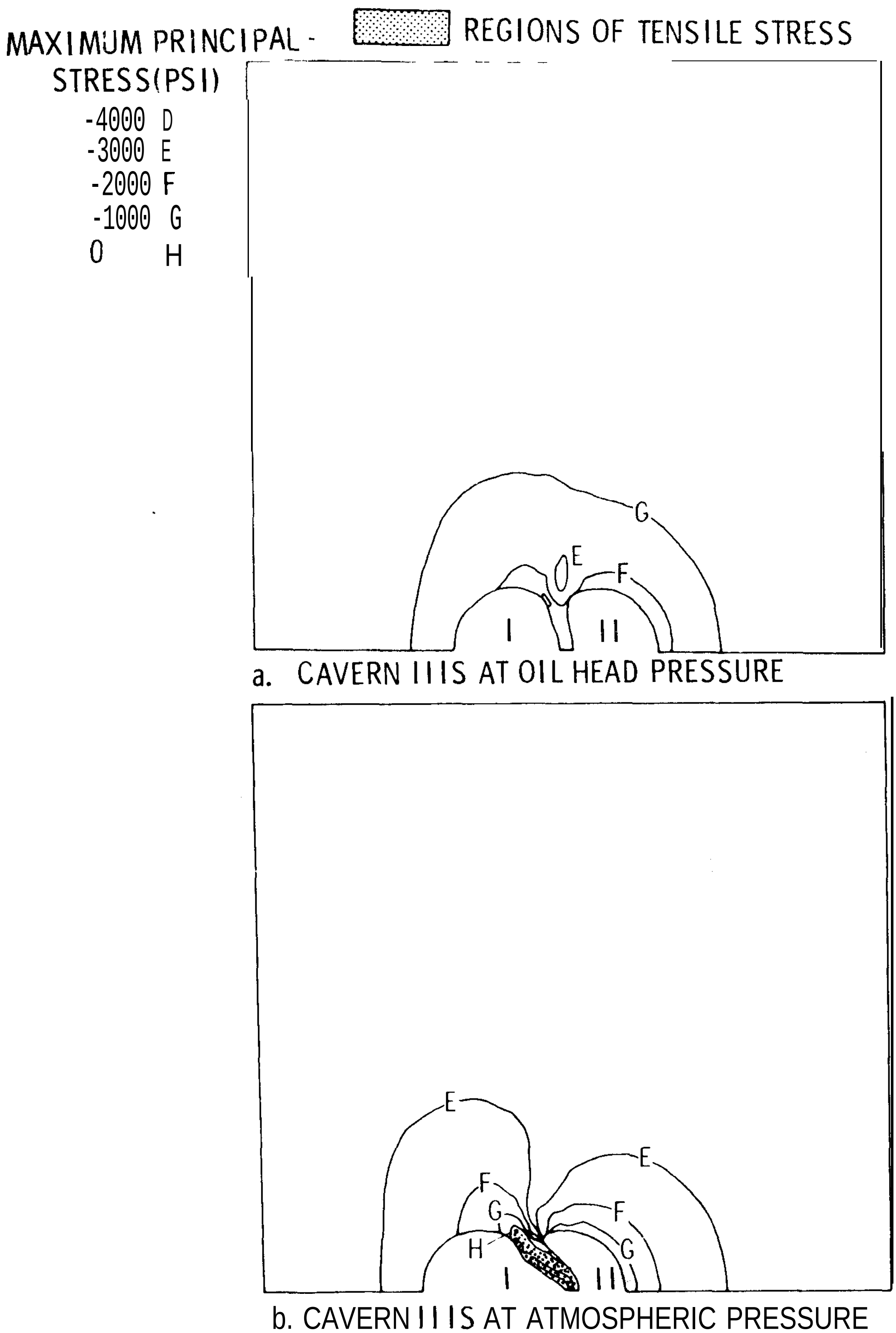


FIGURE17. MAXIMUMPRINCIPALSTRESSCONTOURS FOR HORIZONTAL IDEALIZATION, P/D = 0.2

CONCLUSIONS AND RECOMMENDATIONS

Elastic-plastic finite element stress analyses were performed on models of the adjacent cavern interaction problem. Two cylindrical caverns (300 foot diameter and 600 foot height) at a depth of 3200 feet from the ground surface to the cavern roofs were analyzed for various separation distances. One cavern was maintained at the pressure of a brine column from the ground surface while the pressure in the second cavern was decreased to (a) the oil head pressure and (b) atmospheric pressure. The results from these analyses indicate that a 150 foot web thickness (P/D = .5) is stable for both pressure levels while a 60 foot separation (P/D = .2) is unstable in each case. While some caution is required in the generalization of these results it is concluded that they do indicate which situations need further in depth study. In particular, a number of the ESR caverns have spacings similar to or less than the 150 foot web thickness. Other ESR cavern spacings will become less than this value after only a few cycles of use as a result of leaching caused by the fresh or raw water injection method planned for oil extraction. Two recommendations are made for caverns with current or future P/D ratios of less than 0.5:

(1) Pressures in such adjacent caverns should be carefully maintained at the same level to prevent excessive stress in the separating web.

(2) Further analysis employing more accurate representations of cavern shapes, sizes, and depths as well as site specific material properties are necessary to more accurately predict safe operating conditions for these caverns.

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West Hackberry Site, Cavern 7.

West Hackberry Site, Cavern 8.

West Hackberry Site, Cavern 9.

West Hackberry Site, Cavern 11.

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